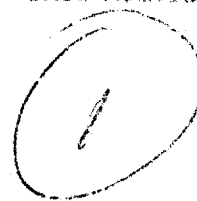


November, 1970
DMIC Memorandum 251



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APPLICATIONS AND POTENTIAL OF
THERMOMECHANICAL TREATMENT

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APPLICATIONS AND POTENTIAL OF THERMOMECHANICAL TREATMENT*

H. J. Henning**

INTRODUCTION

Thermomechanical treatment (TMT) has been the subject of perhaps more than 1000 papers and reports accounting for over a half-million pounds, and probably closer to one million pounds of papers, data sheets, and comprehensive reports. Several million dollars have been spent by industry and government in evaluating the fundamentals of TMT. Doubtless, more money will be spent in the '70s. A question worth asking is--When are we going to get down to the task of applying these fundamentals in the preparation of actual products? Certainly, there are enough technical data available to demonstrate what can be expected in the way of improvements in hardware performance.

Take the agenda of The Technical Cooperation Program meeting on TMT as an example; only one or two of the papers considered TMT practices in relation to a specific production or preproduction product application. The rest of the papers provided only more fundamental background on TMT, leaving the choice of applications to the audience.

After conducting a reasonably complete review of the literature on the subject, and reviewing results of several projects on TMT at Battelle Memorial Institute, the author has concluded that the work on TMT in the '70s would be best spent on applications, with some diminished effort directed to fundamental aspects.

The objective of this memorandum is to present an overview of thermomechanical treatments as they apply to several metal-base systems and to point out where the TMT processes seem either practical or impractical in their application to production hardware. Toward this objective, one should recognize two basic assumptions: (1) that TMT practices offer means of developing unusually favorable mechanical properties not obtainable by hot-working and heat-treatment processes alone, and (2) that part-shape capability in TMT is limited by roughly the same criteria that limit the cold-working of metallic hardware.

Consistent with Assumption (1), significant improvements through TMT in such properties as tensile strength, impact resistance, low-cycle fatigue, and fracture toughness are reasonably well documented. Simultaneous improvements in several of these properties are sometimes observed. Most often, however, the improvements in strength properties are obtained at some expense of ductility and toughness. In any case, a wealth of data is available to show how the properties are interrelated after various TMT procedures.

Assumption (2) indirectly helps to identify the kinds of shapes to which TMT can be applied. For example, sheet, plate, bar, rod, and reasonably simple cross sections like C's, T's, U's, and L's can all be cold drawn or cold rolled to impart special properties. These are the same shapes that can be processed by thermomechanical treatments. Similarly, some extruded shapes are also amenable to TMT. All of these shapes are characterized by deformation occurring predominantly in one direction along a common axis.

Cold-working processes are not readily applied to complex shapes where the metal has to flow along three axes at the same time. For example, certain types of closed-die forgings cannot be cold worked without resorting to multiple-step die sequencing to develop one direction of flow followed by flow in other directions in one or more succeeding die stages. The same practical restrictions are placed on TMT. It is very difficult to cold forge a complex rib-and-web part. It is even more difficult to apply TMT in this situation. Consequently, the benefits of TMT are obtainable in a variety of part shapes commonly produced by cold finishing such as:

Rolled Products--bar, rod, flats, plate,
sheet

Extruded Products--cylinders, tubes, L's
T's, U's

Forgings--disks, flats, rounds, squares
cups.

These should be considered as applications rather than limitations.

There is a size limitation on products that can be cold formed; TMT places an even more stringent size limitation on the same products. Time is the most important factor, because the materials being TMT processed are generally in a metastable condition--ready to undergo a favorable or unfavorable metallurgical change. The more stable the material, the broader the size range of parts that can be processed by TMT. The practical weight limitations indicated in Figure 1 for various products are considered as realistic considering today's TMT technology. Larger parts that are to be processed by TMT require materials of particular structural stability. It should be noted that the greatest weight capability shown in Figure 1 for sheet and plate is for carbon-steel plate (cross-hatched portion of bar), which is commonly warm rolled to strengths substantially higher than those of hot-rolled products. The other practical weight limit for sheet and plate (clear portion of bar) is considered realistic for alloy steels.

THERMOMECHANICAL TREATMENT OF SPECIFIC ALLOYS

To date, most investigations of TMT have been concerned with the alloys listed in Table 1. This listing of materials represents an approximate ascending order of attention that was given to the respective TMT processes during the '60s. An increasing percentage of more recent R&D efforts on TMT is being directed to the nickel-base alloy systems.

* Adapted from a talk given by the author at a meeting of Sub-Group P on Materials, Working Group on Metals, of the Technical Cooperation Program, London, April, 1970.

**Associate Chief, Metalworking Division, Battelle Memorial Institute, Columbus, Ohio.

TABLE 1. MATERIALS SUBJECTED TO EXPERIMENTAL TMT DURING THE 1960's

Material	Description of TMT	Objective	Remarks
Carbon and low-alloy constructional steels	Strain aging accomplished by warm finishing	Higher strength	
Low- and moderate-alloy high-strength steels	Hot-cold working or ausforming	Higher strength	
Maraging steels	Warm working by controlling reductions at lower end of hot-working temperature range	Increased ductility, reduced grain size	TMT controls both grain size and precipitation reactions
Tool steels	Hot-cold working and/or ausforming	Improved toughness	
Bearing steels	Hot-cold working	Improve fretting fatigue life of bearings	
High-speed steels	Hot-cold working above the nose of the time-temperature transformation (TTT) curve	Improved wear resistance and dimensional stability	
Nickel-base superalloys	Controlled reductions and temperatures specifically to alter metallurgical structure and precipitation hardening	Increased strength, increased resistance to low-cycle fatigue	
Titanium alloys	Working at specific temperatures and reductions to control microstructure	Optimization of mechanical properties	Properties of all-beta alloys depend on controlled warm reduction
Aluminum alloys	Warm or cold TMT processes to alter residual stresses	Reduce sensitivity to stress corrosion	
Iron-base superalloys			Respond unfavorably to TMT

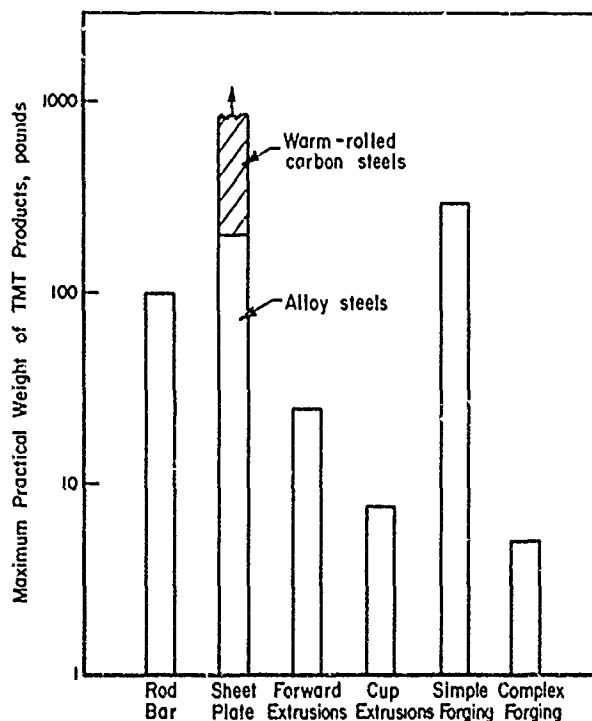


FIGURE 1. PRACTICAL WEIGHT LIMITS ON VARIOUS TMT PRODUCTS

Many excellent papers have been prepared to explain the details of changes occurring in metals during TMT processing. In essence, the accepted view is that TMT combines the attributes of three classical hardening mechanisms--work hardening, structural refinement, and metallurgical transformation. These mechanisms are active to greater or lesser degrees in each material. The warm strain essentially hastens normal metallurgical reactions.

Low-Carbon Steels

The low-carbon steels are generally not transformable to martensite. The TMT processes are limited to controlled warm rolling to produce strain-aging effects. Warm strain accelerates precipitation of nitrides and carbides, which strengthen the ferrite phase. Thus, the steels are simultaneously strain hardened and precipitation hardened--both very classic phenomena.

At least three steel mills in the United States offer structural carbon steels finished with proprietary warm-rolling practices. The steel plates are often 25 to 30 percent stronger than their hot-rolled counterparts.

Aluminum Alloys

In aluminum alloys, 1651 or 1652 treatments are used to modify the strength and the residual-stress system in the sense that controlled reduc-

tions are used to develop special properties after aging, these widely accepted practices could be termed TMT processes. Such treatments are effective in the higher strength aluminum alloys because they are in a metastable condition in the solution-heat-treated condition--they age harden significantly at room temperature.

The TMT of high-strength aluminum alloys provides some minor strengthening, but more important, it increases their resistance to stress-corrosion cracking.

Maraging Steels

The metallurgical reactions occurring in the hot working of maraging steels are somewhat characteristic of TMT. Mostly because of the high-nickel content, the austenite phase is very sluggish in its recrystallization reaction even during deformation at temperatures in the vicinity of 1700 F. The effects of prior strain are retained even after the normal solution-heat-treatment cycles at 1500 and 1600 F. This residual strain hardening has an influence on the subsequent precipitation reactions occurring during aging and generally results in components having modest improvements in strength, ductility and impact resistance compared with components that are recrystallized at temperatures above 1900 F before solution heat treating and aging.

Titanium Alloys

The classical alpha-to-beta structural relationships in titanium alloys can be modified only by varying the hot-working cycles to provide the desired proportions and distributions of each phase. From the metallurgical viewpoint, the control of titanium microstructure through controlled combinations of reduction and temperature represents a TMT process. Defined as such, it is one of the most widely used production applications of the TMT processes.

The all-beta alloys are dependent on TMT processing for final strength performance. For example, the familiar Ti-13V-11Cr-3Al alloy is one that requires controlled reductions at temperatures in the vicinity of 1450 F before optimum properties can be obtained on subsequent aging. Both strength and ductility are increased by this warm-working practice which has a major influence on the speed and uniformity of the precipitation reaction during aging.

Experience with the titanium alloys has shown that accurate control of both processing temperatures and reductions is necessary to achieve the desired properties in the final product. The control is similar to that required in TMT processing of other alloy systems.

Nickel-Base Alloys

Recent research and development work with TMT has been directed to the task of obtaining improvements in certain properties of high-strength, nickel-base superalloys; a good example is General

Electric's program on Udimet 700 and René 95.* Depending on the amount of warm deformation, for example, the tensile strength of Udimet 700 at 1000 F can be increased from about 190,000 psi in the normal solution-treated-and-aged (STA) condition to over 250,000 psi after TMT consisting of controlled reductions on components that have been previously solution annealed. The reductions are generally performed at intermediate temperatures (1550 to 1900 F) where some precipitation of carbides normally occurs. The warm working accelerates the precipitation reactions and provides for a more uniform distribution of carbides during aging. The strain apparently provides a tremendous increase in the number of sites available for carbide precipitation, thereby reducing carbide enrichment at the grain boundaries. A variety of TMT cycles are being studied. Most provide dramatic increases in room-temperature strengths of these alloys. This improved strengthening is maintained on heating to temperatures of up to about 1400 F. At temperatures above 1400 F, the treated alloys may actually be weaker than those that were not given TMT.

As one might expect, the strain energy resulting from TMT may accelerate elevated-temperature metallurgical reactions; hence, reductions in creep resistance may be encountered at temperatures higher than about 1450 F.

Two leading aircraft-engine builders have expressed confidence that TMT will be useful for obtaining substantial increases in design strengths of Udimet 700 and René 95--especially low-cycle fatigue strengths. In support of this contention, data reviewed so far by the author certainly looks promising.

In all probability, the upper temperatures design strengths for TMT hardware will be reduced slightly from those for the normal STA products because of the decreased creep resistance. However, as applied to a turbine disk for example, this reduction would be significant only for the outer rim--a relatively small proportion of the total part. The rest of the disk is cooler anyway, and the application of TMT should permit significant weight reductions in the webs and hub.

Potential higher strength materials for turbine disks provide part of the incentive for concentrating on TMT. Nickel-base superalloys for aircraft-engine applications are one material class for which the '70s will probably witness a substantial increase in the application of TMT processes.

High Alloy Steels

From the metallurgical viewpoint, it is convenient to consider tool steels, bearing steels, and high-speed steels as a group, because the TMT practices for all of them are similar, and include the following steps:

* Nominal Compositions

	Co	Cr	Mo	Al	Ti	Zr	B	Cb	W	Ni
Udimet 700	15	15	4	1	3	0.04	0.02	--	--	Bal
René 95	8	15	4	3.5	2.5	--	0.01	3.5	3.5	Bal

- (1) Austenitize at temperatures normal for hardening the alloy
- (2) Cool to about 1400 to 1450 F
- (3) Deform, with reductions of 20 percent or more
- (4) Quench in a suitable oil or salt
- (5) Temper to the desired hardness.

The responses to TMT of the different steels are slightly different however. The carbide-rich high-speed steels behave somewhat like the nickel-base alloys in that TMT enhances the uniformity of carbide precipitation during both deformation and tempering, and the end product is harder than that obtainable without TMT. For the tool steels and bearing steels, however, even though the carbide precipitation occurring during deformation is enhanced by TMT, and provides for a higher as-quenched hardness, the hardness of the TMT-processed end product is not significantly higher than that obtainable by tempering, where secondary hardness peaks are normally observed.

The most promising prospects for TMT processes in this group of steels appear to fall into three areas:

- (1) Resistance to contact fatigue is improved substantially in the high-alloy bearing steels
- (2) The toughness or impact resistance of high-speed steels increases somewhat
- (3) The hardness of some of the medium-carbon tool steels can be increased significantly.

TMT of special-quality bearing races seems to represent the most promising application. Otherwise, it is doubtful that there will be any significant use of TMT toward improving these steels, partly because the steels are so hard and, hence, difficult to finish after TMT.

It is likely that the rapid growth of electroslag-melting processes, through improved cleanliness, will offer a more practical alternative method than TMT for enhancing the properties of these steels.

Alloy Steels

By far the most extensive research and development work on TMT has been directed to the broad group of alloy steels containing modest levels of alloy elements and carbon, levels between 0.30 and 0.50 percent. Perhaps 10 to 50 grades fall within this category of steels. Most of them are typified by reasonably good hardenability, and usually have a deep bay in their time-temperature transformation (TTT) curves, as typified by Figure 2.

The TMT consists of either hot-cold working steels above the "nose" of the TTT curve or ausforming in the deep-bay region. A typical cycle consists of:

- (1) Austenizing at normal hardening temperatures
- (2) Cooling to either the hot-cold working or the ausforming temperature range
- (3) Deforming, with reductions of 20 percent or more

- (4) Quenching in a suitable oil or molten salt
- (5) Tempering to the desired hardness.

At hot-cold working temperatures, the forming forces are about 2 to 3 times those for hot working. However, at ausforming temperatures, the forming forces are similar to those for typical 18Cr-8Ni stainless steels, or closer to 5 times those for hot working.

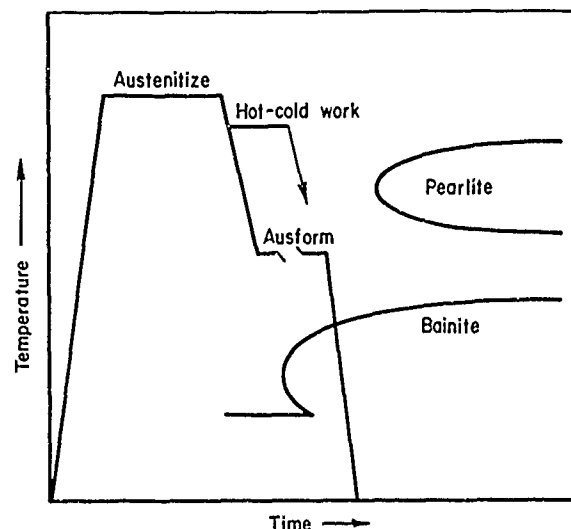


FIGURE 2. SCHEMATIC COMPARISON BETWEEN HOT-COLD WORKING AND AUSFORMING OF ALLOY STEELS

The U. S. company most active in striving TMT of alloy steels during the '60s was the Ford Motor Company. Although several other manufacturing firms and research centers have been evaluating TMT, Ford seems to have gone further than most in applying the processes to actual hardware. For example, Ford's Aeroneutronics Division has been applying TMT to the task of preparing dual-hardness armor plate having unusually good toughness. Ford's research center has been evaluating hot-cold working as a means of producing lighter weight leaf springs. Three sets of truck springs are compared in Figure 3, which shows how TMT permits reductions in the overall weight of the springs and the number of leaves. The upper assembly on each pair is the standard (no TMT) and the lower represents the spring assembly redesigned through TMT and requiring fewer leaves to carry the same load. The lower example shows that only six TMT processed leaves are required where 10 were formerly needed. Recent information from Ford indicates that the TMT springs have definitely outperformed the standards in both bench tests and field tests. Fatigue strength of the TMT-processed springs was more than 20 percent higher than that of the standards. Although the use of TMT for this application appears to be technically feasible, application of TMT processing would require a substantial investment in new equipment, and Ford has not yet begun to use the process for production.

TMT research at Battelle has included four programs on the TMT of alloy steels—one for the Air Force and three for private industry. Similar to that of other TMT research programs, the objective generally has been to obtain higher hardnesses and higher strength components. For example, Table 2 shows some results from Battelle research, and compares typical tensile properties for three different

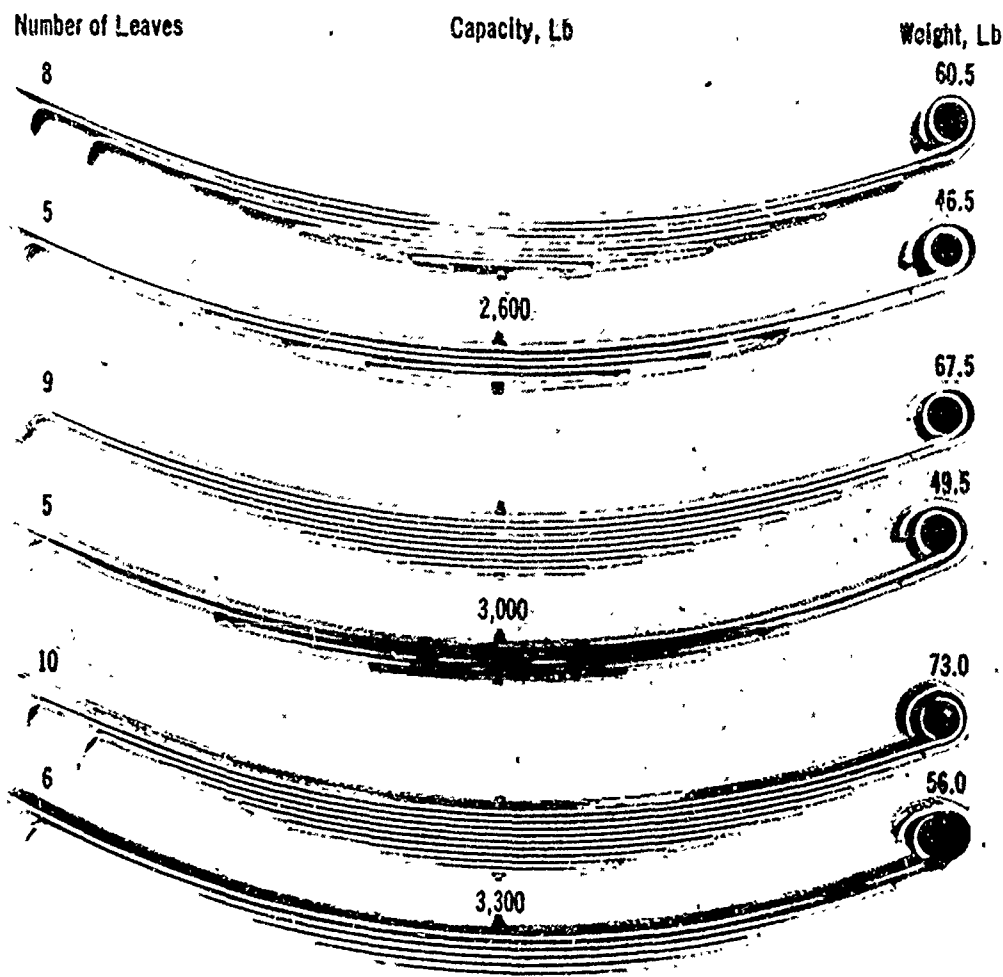


FIGURE 3. COMPARISON OF CONVENTIONAL AND TNT LEAF SPRING ASSEMBLIES OF SAE 5150 STEEL SHOWING REDUCTIONS IN BOTH WEIGHT AND NUMBER OF COMPONENTS

Lower spring in each group is designed for the capacity shown, using steel processed by TNT.

TABLE 2. PROPERTY IMPROVEMENTS ATTAINABLE BY AUSFORMING AND HOT-COLD FORGING

Steel	Condition	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Reduction in Area, percent
H-11	Conventional	320	270	10
H-11	Ausforged at 1000 F	390	350	57
D6AC	Conventional	305	255	13
D6AC	Ausforged at 1000 F	390	335	22
4340	Conventional	290	240	8
4340	Hot-cold forged at 1400 F	320	275	35

steels processed conventionally with those for the same steels processed by TNT. While greatest strengthening is observed for the ausforged D6ac* and H-11* steels, the hot-cold forged 4340* grade is also strengthened, by roughly 10 percent--still an attractive improvement.

In one of the Battelle programs, the processing and properties of hot-cold work cycled material were compared with those of material that was ausforged with the discovery that working provided strengthening similar to that from ausforging, provided sufficient deformation was applied. As shown in Figure 1, a 40 percent reduction by hot-cold working results in a hardness response similar to that produced by a 20 percent reduction by ausforging.

* Nominal Compositions:

	C	Mn	Si	Cr	Ni	Mo	V
H-11	0.40	0.25	0.8	5.0	-	1.3	0.4
4340	0.40	0.50	0.3	0.7	1.7	0.2	-
D6ac	0.45	0.60	0.3	1.0	0.7	1.0	0.1

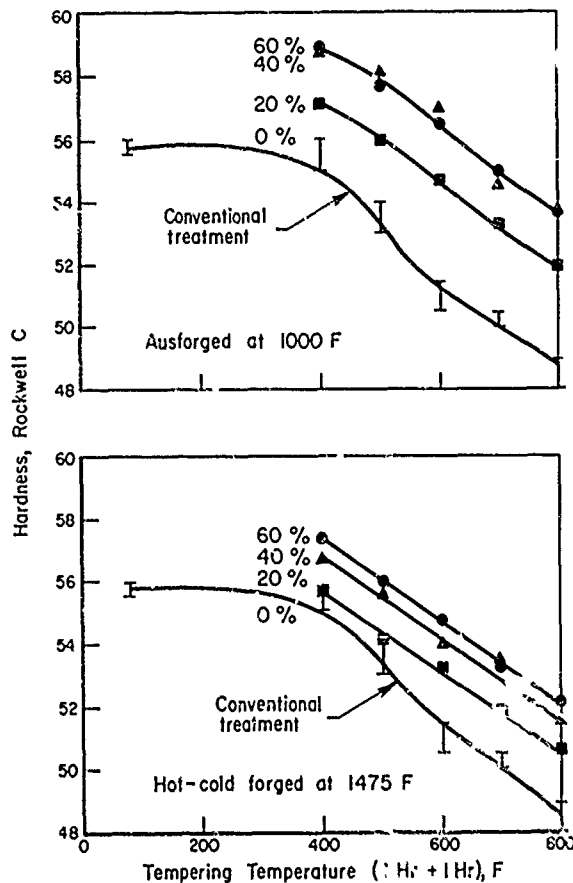


FIGURE 4. EFFECT OF HOT-COLD FORGING OR AUSFORMING BY VARIOUS REDUCTIONS ON THE TEMPERING RESPONSE OF 4340 STEEL.

The Battelle research also indicated that the hot-cold working cycles were more readily controlled, partly because the workability of the steels was better at the hot-cold working temperature than at ausforming temperatures. At typical ausforming temperatures, it was difficult to judge the work-piece temperature during forging, because it was in the black-heat range. A knowledge of the temperature is important, because it is difficult to predict when to stop forging to prevent cracking caused by excessive cooling and the resulting transformations. Temperature changes occurring during hot-cold working are quite visible, hence easier to control.

A comparison of hot-cold working with ausforming is presented in Table 3. While it is true that the highest possible strengths are achievable through ausforming, the need for precise control of both time and temperature will continue to limit applications of ausforming under production conditions.

Another advantage of hot-cold working cycles over ausforming is that the ITT curve of the steel need not have a very deep bay, hence, lower cost alloys can be hot-cold worked.

Perhaps the most attractive features of the processing of alloy steels with IMT are improved

impact resistance and the greatly improved fatigue strengths achievable. For example, the Battelle studies showed that the fatigue life of forgings was increased substantially by hot-cold working. As shown in Figure 5, fatigue life of hot-cold forged 4340 steel components was several times that for conventionally heat-treated components. Similar improvements were noted for specimens both longitudinal and transverse to the forging direction.

One example of a part that has been successfully hot-cold forged under production conditions is shown in Figure 6. The figure illustrates the sequences used in forging an engine mount from the fillet stage. The parts were hot-cold forged in the finish-forging operation.

TABLE 3. COMPARISON BETWEEN HOT-COLD WORKING AND AUSFORMING

Ausforming	Hot-Cold Working
Maximum strengthening	Intermediate strengthening
Moderate forming forces	Low forming forces
Precise process controls	Practical process controls
Higher alloys--deep bay	Lower alloys
Special equipment	Normal equipment

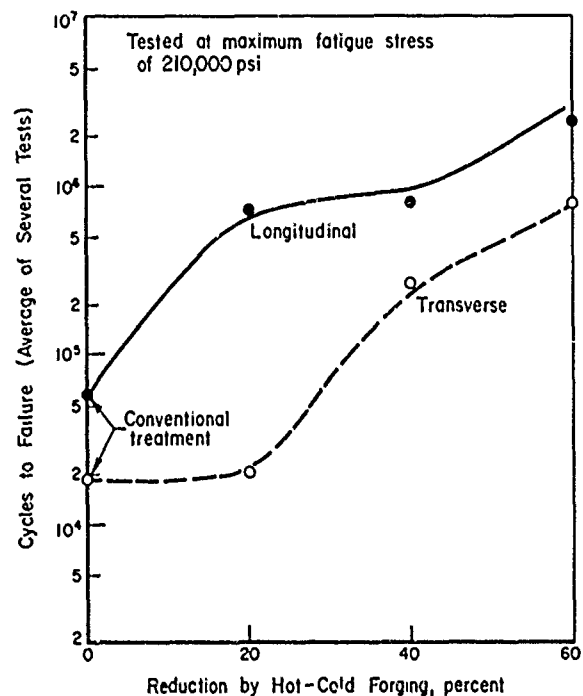


FIGURE 5. DATA SHOWING THE INFLUENCE OF PROGRESSIVELY LARGER HOT-COLD FORGING REDUCTIONS ON THE FATIGUE LIFE OF 4340 STEEL.

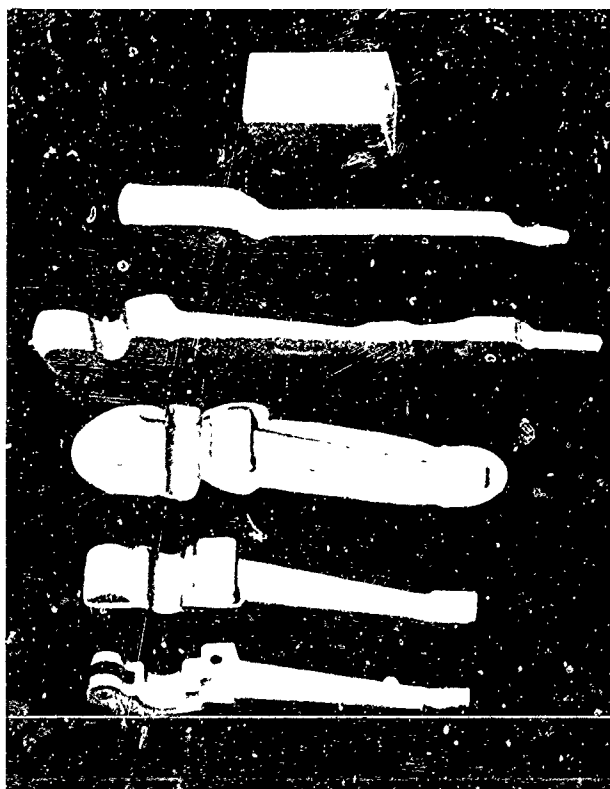


FIGURE 6. STEPS IN THE MANUFACTURE OF A 4340 STEEL ENGINE MOUNT BY HOT-COLD FORGING

One of the cycles used for hot-cold forging the engine mount is illustrated in Figure 7, which shows that all deformation was done at the hot-cold working temperature. Eventually, the first two forging steps were done hot (2150 F) and the process still provided enough deformation at about 1400 F to obtain the improvements in strength corresponding to about a 40 percent reduction.

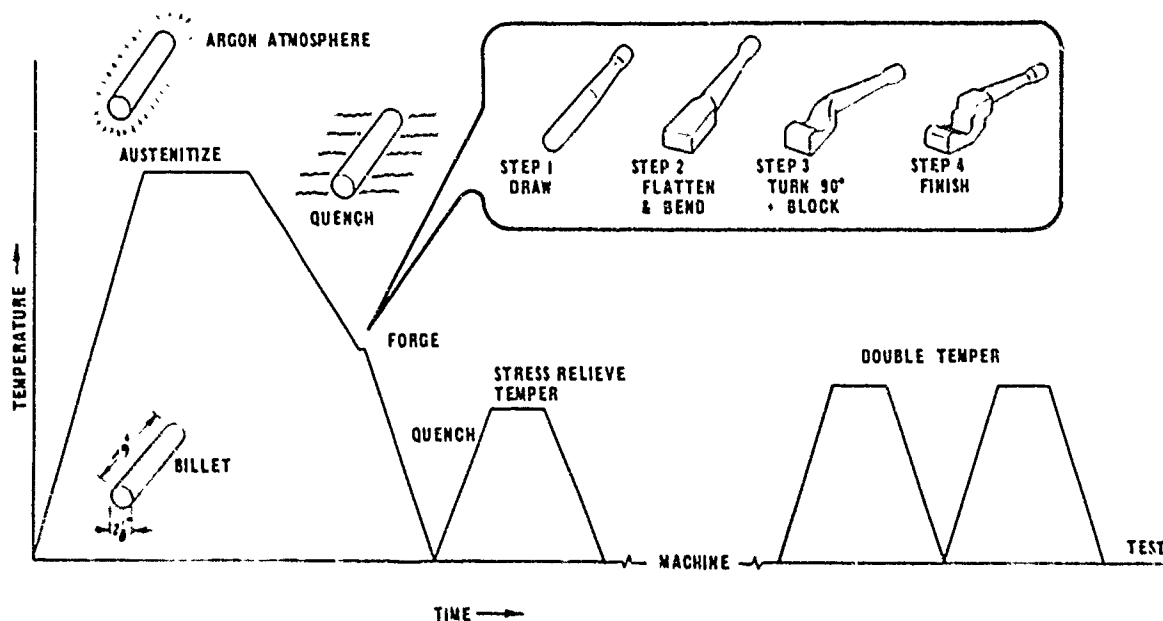
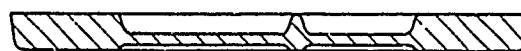
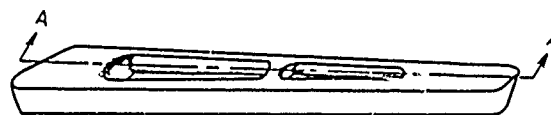


FIGURE 7. ILLUSTRATION OF PROCESSING SEQUENCES USED IN HOT-COLD FORGING OF ENGINE MOUNT

In the United States, several current programs are aimed at applying TMT to specific steel hardware components. At the Ladish Company, for example, several 36-inch-long rib-and-web forgings, illustrated in Figure 8, have been hot-cold forged with some success. Of particular significance in that program are the substantial improvements in fatigue strength being obtained in reasonably large parts, as shown in Figure 9.

The hot-cold forged part in Figure 8 represents a practical limit for shape complexity of TMT-processed components.

Reviews of the literature from the United Kingdom, West Germany, Canada, and the U. S. S. R. indicate that TMT research in those countries is producing property improvements in steel similar to those reported in the United States. Some of the emphasis on the foreign programs is being placed on different aspects of TMT; nonetheless, it is quite clear that so much data already exists on TMT that almost any new research program aimed strictly at collecting fundamental data will very likely duplicate much of the work already done.



Section AA

FIGURE 8. RIB AND WEB STRUCTURE HOT-COLD FORGED AT LADISH

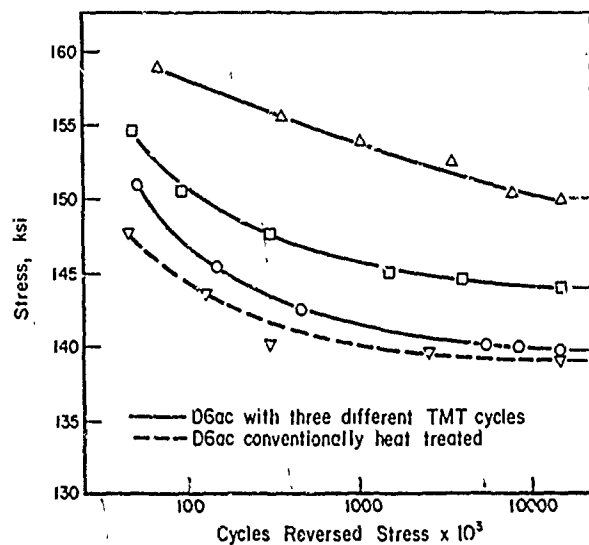


FIGURE 9. COMPARISON OF REVERSED-BEND FATIGUE STRENGTHS OF b6ac WITH VARIOUS TMT CYCLES

FORECAST FOR THERMO-MECHANICAL TREATMENTS

The normal (without TMT) processing of some alloy systems routinely incorporates the same degree of control on forming temperatures and reductions that is required for TMT processes; hence, the control requirements for TMT offer no real barriers to its application.

Hardware development programs are becoming increasingly concerned with specific improvements in fatigue strength and fracture toughness available from TMT, and one may expect that less emphasis will be placed on the capabilities of achieving the highest possible hardness with TMT.

Once a few applications have been proven out for relatively small hardware items (under 25 pounds), future programs will be aimed at applying TMT to larger parts. If the items are to be fabricated of low-alloy steels, a need will arise for alloy modifications aimed specifically at raising the austenite recrystallization temperature. A broader hot-cold working temperature range will be necessary so that the larger parts can be hot-cold worked with reasonable cycles. Increasing the levels of silicon and nickel are known approaches to increasing the austenite recrystallization temperature of low-alloy steels. Perhaps the ideal steel for hot-cold working will contain the basics of the b6ac grade but with higher levels of both nickel and silicon.

It appears that PMI processes will continue to be limited in application by important difficulties with:

- (1) Machining the hard PMI product
- (2) Welding
- (3) Achieving uniform deformation in complex shapes.

PMI-processed alloys, particularly the steels, are very hard, but the nonmechanical machining methods

for metal removal provide an alternative to conventional machining.

Welding the TMT product removes the beneficial effects of the TMT; furthermore, the weld zone cannot be heat treated for proper grain refinement.

Since the forming forces are higher and the austenite phase is actually strain hardening during TMT processing, there are practical limits on steel shapes producible.

It would be inappropriate to conclude that only very little basic research needs to be done on TMT. However, so much research has been done to date, it seems logical that future developmental work should concentrate on evaluating potential applications of TMT against a framework of limitations that are now reasonably well identified.

The basic shapes that are amenable to TMT are given in Table 4, which also gives some examples of hardware articles that could be prepared from them.

TABLE 4. POTENTIAL APPLICATIONS OF TMT

Basic Shapes	Articles
Extruded tubing	Small bearing races
Forged disks	Turbine wheels
Rolled or forged flats	Leaf springs
Rolled or extruded shapes	Special structurals
Forged cups	Large bearing races
Rolled rounds or squares	Torsion-bar springs
	Ball bearings
	Special tools
Forged blocker shapes	Air frames

The future applications of TMT will depend largely on the ingenuity of those in the manufacturing community who are willing to capitalize on the benefits.

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